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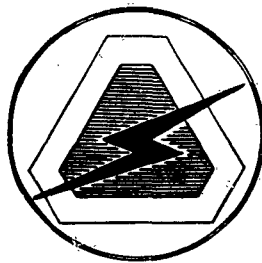
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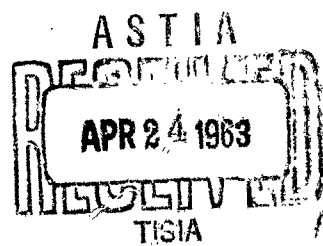
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DEVELOPMENT OF A QUALITY MEASUREMENT FOR VARACTOR DIODES
AT MICROWAVE FREQUENCIES

Frank P. Senko



November 1962



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UNITED STATES ARMY
ELECTRONICS RESEARCH AND DEVELOPMENT LABORATORY
FORT MONMOUTH, N.J.

U. S. ARMY ELECTRONICS RESEARCH AND DEVELOPMENT LABORATORY
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November 1962

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AT MICROWAVE FREQUENCIES

Frank P. Senko

DA Task Nr. 3A99-21-001-02

ABSTRACT

A technique is described for characterizing the microwave varactor diode at microwave frequencies. Basically, this is a reflectometer type of technique that permits reasonable accuracy and speed of measurement without the need for standard Smith Chart plots and/or auxiliary (substitute) devices. The varactor parameters of major importance are specified. Included also are the limitations of the method.

U. S. ARMY ELECTRONICS RESEARCH AND DEVELOPMENT LABORATORY
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DEVELOPMENT OF A QUALITY MEASUREMENT FOR VARACTOR DIODES AT MICROWAVE FREQUENCIES

INTRODUCTION

The development of the variable capacitance microwave diode (varactor) was accompanied almost simultaneously by the development of many circuit applications for this device such as low-noise amplifiers, modulators, switches, and frequency multipliers.¹ Usually before such applications can be produced, the circuit parameters, especially of the controlling device, must be known and specified within certain limits. As various manufacturers began to develop and/or apply the varactor diode, each tended to develop its own method or technique for characterizing the diode. To date, there are several different techniques and many variations of similar characterization techniques with considerable disparity among some of them. Currently, the IRE Task Group on High-Frequency Diodes (28.4.13) is concerned with the establishment of varactor measurement standards which may result in alleviating this problem.

The Army Signal Corps pioneered in the development of the varactor diode. An immediate need arose to determine the technical requirements and characterization techniques for this device. This was accomplished under Signal Corps Contract DA-36-039-SC-78236 with Microwave Associates and applies a concept developed by N. Houlding.

This report describes the technique and analyses of the Signal Corps method of characterizing the varactor diode at microwave frequencies and contains appropriate supplementary information.

BACKGROUND

A varactor is defined as a two-terminal semiconductor device used as a voltage dependent capacitor. All nonlinear characteristics and most losses of typical varactors are localized in the small semiconductor element. Since the size of the element is a small fraction of the wavelength of the electromagnetic radiation with which it is to interact, the element may be considered as a two-terminal lumped nonlinear circuit element embedded in a linear network. This linear network may be represented by lumped and/or distributed parameters. The cartridge (or package) in which the element may be supplied often contributes significantly to the properties of the linear network.

A useful equivalent circuit for the active element of a varactor is shown in Figure 1. This circuit includes two voltage-dependent lumped parameters, C and G . At high frequencies the shunt conductance G is negligible compared to the capacitive reactance; therefore, for this report, the simplified equivalent circuit in Figure 2 is provided. There are other known effects such as frequency dependence of C , G , and R_s (equivalent series resistance), and current dependence of R_s . These effects are mentioned only for scientific interest; they are not active under the conditions of measurement discussed in this report. Since the package impedance that contributes to the linear network of the whole device may be strongly frequency dependent, the measurement method described below requires a constant frequency. In addition, R_s , in Figure 2, is considered to include losses in the package, leads, test holder, and filter through which dc bias is introduced. Package and test-holder reactances are purposely not included in the equivalent circuit so that a lower and more practical quality rating will result.

QUALITY MEASUREMENT (MICROWAVE)

General

A varactor applied as a pure variable capacitance has its performance limited by the magnitude of its equivalent series resistance R_s . A measure of this limitation is expressed by the varactor quality factor Q , which is equal to the ratio of reactance to resistance:

$$Q = \frac{X_c}{R} = (2\pi fCR)^{-1}.$$

The quality of a varactor may be specified by stating its Q at a given frequency or by designating the frequency at which Q becomes unity.

For this method of measurement, the figure of merit for a varactor will be $f_c = (2\pi R_s C_{min})^{-1}$ where f_c is the cutoff frequency defined by $Q = 1$, and C_{min} is the capacitance at the reverse breakdown voltage V_b , as suggested by Uhler.¹ The cutoff frequency measurement and the (low-frequency) capacitance-voltage relationship curve are sufficient for most microwave applications. The simple equivalent circuit (Figure 2), defined above, implies that $f_c = Q_m f_m$, where Q_m is the Q at the measurement frequency f_m (assuming there are no frequency dependent losses).

The chief interest in varactor diodes has been in their use at microwave frequencies where the most influential factors are the capacitance value and the Q . At frequencies comparable to the cutoff frequency, the varactor leakage conductance may be neglected, as in the previous discussion, and the low- Q measurements can be made which are easier to execute and inherently more accurate. Thus, the measurement method described below (a reflectometer type of technique) permits the determination of f_c and R_s from microwave measurements of Q and low-frequency measurements of capacitance.

A block diagram of the varactor quality measurement circuit is shown in Figure 3, and the E-H tuner and varactor holder are given in Figure 4. The equivalent measurement network (Figure 5) is assumed to be as shown to the left of terminals T-T; that is, the lossless network, as viewed from left to right, includes a termination matched to a length of input transmission line of characteristic impedance $Z_0 (=R_0)$, followed by a coupler directing rf power toward the load, a (shuttered) reference short, a lossless variable transformer (E-H tuner), a lumped reactance due to the varactor holder, package, and semiconductor capacitance (at bias $V_1 = V_b$) and a variable (lumped) reactance provided by the varactor holder movable short.

Procedure

The measurement procedure is as follows (Figure 3):

1. Loosely couple (about 25-db) signal port 1 down to signal port 3. Then if there is no reflection at port 3, there is negligible signal received at signal port 4. For a constant level of input, the signal level received at port 4 is proportional to the reflection coefficient of the termination at port 3, provided port 4 is matched.

2. For an appropriate bias point, in this case V_b (breakdown voltage defined at $I_r = -10\mu A$), adjust the tuning elements for a minimum reading on the detector; however, to reduce possible ambiguity, first set the movable short S_1 (Figure 4) to an optimum position with the E-H tuner giving negligible transformation. Then it is usually necessary to adjust only S_2 for a good match (minimum reading). If the directional coupler directivity is sufficiently high (> 40 db), this "minimum reading" will correspond to a very low reflection coefficient. The bias voltage is then changed to $-V_2$ and the detector amplifier gain set to give a suitable reading.

3. Replace the varactor with a total reflection by means of a waveguide shutter, and adjust the precision (calibrated) attenuator to give the same reading on the detector indicator. In this way the forward and reflected waves traverse identical line conditions so that most of the line attenuation is compensated. The attenuation change A (ratio of available powers) is related to ΔQ , the change in Q for the change from V_b (C_{min}) to $-V_2$ (C_2). If the varactor capacitance law is known, V_2 may be chosen with respect to V_b so that the value of Q at V_b can be deduced and the attenuator calibrated directly.

Analysis

In the equivalent circuit shown in Figure 5, $Z_L = R_s + j(X_o + \Delta X + X)$ where (1)

Z_L = load impedance

R_s = varactor series resistance, including package and holder resistance (losses)

X_o = varactor capacitive reactance at V_b , including package and holder parasitic capacitance

X = variable reactance of holder movable short

ΔX = change of capacitive reactance of varactor element dependent on ΔV .

If, as stated above, it is assumed that the package and holder losses are equivalent to a lumped resistance in series with the varactor, and stray shunt conductance and series conductance are insignificant, additional lossless transformation may be introduced (E-H tuner), thus transforming what is essentially a lumped constant resistance and a variable capacitance element.

The holder shorting stub and E-H tuner adjustments obtain a perfect match with the bias at V_b and effectively transform to the $(1 + j0)$ point on the Smith Chart (Figure 6). The $(1 + j\Delta x)$ circle on the Smith Chart then becomes the locus of the load impedance graph for changing bias conditions and constant rf matching conditions. Thus, a predetermined change in bias, selected so as to cause a small change in varactor capacitance, will produce a point $(1 + j\Delta x)$ on the Smith Chart.

Assuming ΔX is affected by the same transforming conditions as R_s , the transformed reactance change will be related to the actual change in capacitance in the varactor; i.e., if $Z_o = n^2 R_s$, $\Delta X' = n^2 \Delta X$, and the normalized impedance of the load at the input side of the transformer becomes

$$z_1 = \frac{Z_L}{Z_o} = \frac{n^2 R_s + n^2 j \Delta X}{n^2 R_s} = 1 + j \Delta X \quad (2)$$

where $\Delta X = \frac{\Delta X'}{Z_o}$ is the transformed normalized reactance (of the varactor element) at $-V_2$ and

$z_o = \frac{n^2 R_s}{Z_o} = 1$ is the transformed normalized impedance of the load at condition V_b (matched

condition), but $\frac{\Delta X'}{Z_o} = \frac{n^2 \Delta X}{n^2 R_s}$ is indicated in the reflection coefficient measurement on the line of characteristic impedance Z_o and can be taken as $\frac{\Delta X}{R_s}$ directly, which is obviously ΔQ of the varactor.

From transmission line theory, the relationship between impedance and reflection coefficient is

$$\Gamma = \frac{(Z_L - Z_o)}{(Z_L + Z_o)}$$

and by using z_1 and z_o from above, one obtains

$$\Gamma = \frac{(1 + j\Delta x - 1)}{(1 + j\Delta x + 1)} \quad (3)$$

Equation (3) is rearranged so that one obtains

$$\Delta x = \frac{2}{\left(\frac{1}{|\Gamma|^2} - 1 \right)^{1/2}} \quad (4)$$

But

$$|\Gamma| = \left(\frac{P_r}{P_f} \right)^{1/2} = \left(\frac{1}{A} \right)^{1/2} \quad (\text{Figure 7})$$

where P_f is the local oscillator forward power which is reflected by the waveguide shutter (refer to Section under Quality Measurement, General); P_r is that part of the forward power reflected by the mismatch Δx , due to voltage change $-V_2 - V_b$, and $A = \frac{P_f}{P_r}$ is the precision attenuator change ratio.

Equation (4) can then be rewritten as

$$\Delta Q = \Delta x = \frac{2}{(A - 1)^{1/2}} \quad (4a)$$

To obtain f_c and R_s , the equation for deriving f_c from Q by Uhler's definition is:

$$Q = \frac{1}{2\pi f_c R_s C_{\min}} = 1 = \frac{X_{\max}}{R_s} \quad (5)$$

By measurement

$$\Delta Q = \frac{\Delta X}{R_s} = \frac{X_1 - X_2}{R_s} = \frac{1}{W_m R_s} \left(\frac{1}{C_{\min}} - \frac{1}{C_2} \right) \quad (6)$$

where

W_m = angular frequency of measurement

X_1 = reactance due to C_{\min} .

By taking the ratio of (6) over (5), one obtains

$$\begin{aligned} \frac{\Delta Q}{Q} = \Delta Q &= \frac{\frac{1}{W_m R_s} \left(\frac{1}{C_{\min}} - \frac{1}{C_2} \right)}{\frac{1}{W_c R_s C_{\min}}} = \frac{f_c}{f_m} \left(1 - \frac{C_{\min}}{C_2} \right) \\ f_c = \Delta Q f_m \left(\frac{1}{1 - \frac{C_{\min}}{C_2}} \right) &= \frac{2f_m}{(A - 1)^{1/2} \left(1 - \frac{C_{\min}}{C_2} \right)} \end{aligned} \quad (7)$$

By deriving R_s from ΔQ , Equation (6) can be rewritten as

$$\begin{aligned} \Delta Q &= \frac{1}{W_m R_s C_{\min}} \left(1 - \frac{C_{\min}}{C_2} \right) \\ R_s &= \frac{0.159}{\Delta Q f_m C_{\min}} \left(1 - \frac{C_{\min}}{C_2} \right) = \frac{(A - 1)^{1/2}}{2W_m C_{\min}} \left(1 - \frac{C_{\min}}{C_2} \right) \text{ ohms.} \end{aligned}$$

Example

It is known that the relation between the capacitance and reverse-bias voltage of the varactor element is very closely given by $\left(\frac{1}{C} \right)^n = K(V + \phi)$ where C is the capacitance, V the bias voltage, $n = 3$ for a graded diffused junction, or $n = 2$ for a step junction, and ϕ is a (contact potential) constant. Using this relation, V_2 can always be determined relative to V_b to provide a constant ratio for $\frac{C_{\min}}{C_2}$. Consider, for example, a varactor with $\phi = 0.4$ volt, $n = 3$, and let $\frac{C_{\min}}{C_2} = \frac{4}{5}$. Then $V_2 = 0.512 V_b - 0.2$ volts.

Equations (7) and (8) now become respectively:

$$f_c = 10f_m(A - 1)^{-1/2} \quad (7a)$$

$$R_s = \frac{(A - 1)^{1/2}}{10W_m C_{min}} \quad (8a)$$

The precision attenuator may be calibrated to read f_c directly. By biasing at some other negative voltage V_1 , instead of at V_b , R_s may be measured at some suitable point other than at C_{min} . In fact this method may be used to measure the Q at any bias point. If the varactor f_c is beyond 100 kmc, the increment C_2 should be smaller, for instance $C_2 = \frac{10}{9} C_{min}$ and $f_c = 20 f_m (A - 1)^{-1/2}$; or the frequency of measurement should be made higher.

Some typical varactor values are:

$$f_m = 10 \text{ kmc}$$

$$P_{rf} \text{ (at load)} = 2 \mu w$$

$$C_2 = \frac{5}{4} C_{min}$$

$$f_c = 50 \text{ to } 100 \text{ kmc}$$

$$C_{min} \approx 0.2 \text{ to } 1 \text{ pf}$$

$$R_s \approx 1 \text{ to } 3 \text{ ohms.}$$

The rf voltage should not be greater than about 5 percent of the bias swing ($V_1 - V_2$) or roughly 50 mv. A 25-db bidirectional coupler with a directivity greater than 42 db at x-band is used in the measurement.

Limitations, Advantages, Disadvantages

One obvious limitation to the above technique of quality measurement is the design of the holder in which the varactor is mounted. If the holder is lossy, a lower (than true) quality measurement will result. On the other hand, no special care is required to insure that the test holder and flange fittings present a good match to the transmission line (waveguide), as any such discontinuities will be matched out by the transformation network (E-H tuner and variable short).

As may be seen, this method is accurate, rapid, and straightforward enough to be satisfactory for both laboratory and production measurements. The method is applicable at any microwave, limited only by the design of a lossless transformer-holder combination.

Other limitations follow:

1. Both power and frequency stability are essential.
2. Certain combinations of varactor-holder impedance vs. transformer location may be such that transformation of R_s to Z_0 cannot be effected. The best arrangement would have to be determined experimentally.

3. The method does not characterize (separately) the parasitic reactance (especially inductive) effects of the package, but does include the package losses.

4. The method assumes a constant (frequency and power independent) series resistance.

CAPACITANCE MEASUREMENT (Low Frequency)

It was stated above that only the capacitive reactance of the semiconductor element would be considered in characterizing the varactor diode and that package and holder parasitic reactances would be excluded. Information on the variation of the element junction capacitance with bias is a necessary part of the specification of varactor parameters. The junction capacitance should be measured at low frequency (about 100 kc) where package inductance effects are negligible. For this purpose a simple capacitance bridge, such as the Boonton Electronics Corporation 74CS4 (with built-in bias supply) can be used. The signal voltage across the varactor should be small (about 30 mv).

One method for isolating the junction capacitance is as follows: Assuming that both the capacitance-bias law constant ϕ and n for the varactor are known and the parasitic reactance remains constant, observe the change in total capacitance as a function of bias. The junction capacitance can be obtained from the expression (see Appendix):

$$C_j = \frac{(C_t' - C_t)}{\left(\frac{V + \phi}{V' + \phi}\right)^{1/n} - 1} \quad (9)$$

where

- C_j = the varactor element junction capacitance at reverse bias V
- C_t = the varactor device capacitance measured at reverse bias V
- C_t' = the varactor device capacitance measured at reverse bias V'
- ϕ = the contact potential, a positive (temperature dependent) constant
- n = a positive constant, dependent on junction type.

CONCLUSIONS

Varactor quality can be determined in a number of ways depending upon relative requirements such as accuracy, rapidity, simplicity, intended application, and available instrumentation. This report has shown that a varactor quality measurement which includes package and holder losses can be performed with ease and accuracy at microwave frequencies comparable to the cut-off frequency of the varactor. Assuming the varactor to be equivalent to a variable capacitance in series with a constant resistance, the method determines absolute values of cutoff frequency.

The important parameters to be specified have been defined herein and shown to be as follows:

- a. cutoff frequency
- b. dynamic (microwave) series resistance
- c. breakdown voltage
- d. capacitance at zero and breakdown voltage bias
- e. exact variation of capacitance with bias voltage.

A limitation lies in the method of transforming the line to the varactor junction and this bears further experimentation.

For maximum accuracy, the method developed should be applied at the highest possible microwave frequencies within the capability of the available Laboratory equipment.

REFERENCE

1. Uhlir, A., Jr., "The Potential of Semiconductor Diodes in High-Frequency Communications," Proc. IRE, Vol. 46 (June 1958).

APPENDIX

JUNCTION CAPACITANCE ISOLATION

The following is a derivation of expression for isolation of junction capacitance versus reverse bias for a varactor semiconductor element. The relation between capacitance and reverse-bias voltage is shown (by W. Shockley) to be very closely given by:

$$C_j = \frac{K}{(V + \phi)^{1/n}}$$

taking $C_t = C_p + C_j$, where C_p = parasitic capacitance and V' respectively becomes:

$$C_t = C_p + \frac{K}{(V + \phi)^{1/n}} \quad \text{and} \quad C_t' = C_p + \frac{K}{(V' + \phi)^{1/n}}$$

or

$$C_t = C_p + Kf(v) \quad \text{and} \quad C_t' = C_p + Kf(V')$$

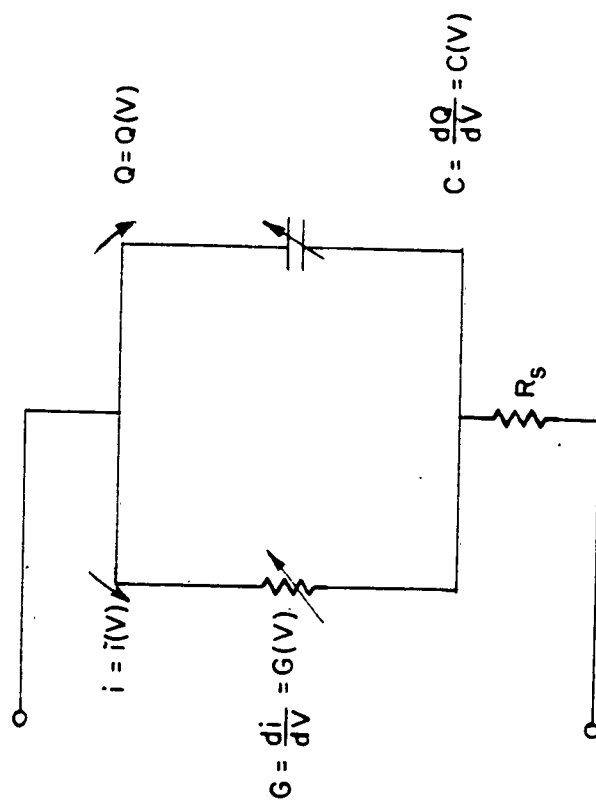
K , ϕ and n are constants.

Solving for K :

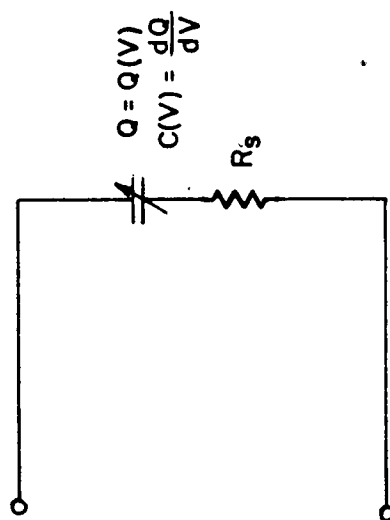
$$K = \frac{\begin{vmatrix} 1C_t \\ 1C_t' \\ 1f(v) \\ 1f(v') \end{vmatrix}}{\begin{vmatrix} 1C_t \\ 1C_t' \\ 1f(v) \\ 1f(v') \end{vmatrix}} = \frac{C_t' - C_t}{f(v') - f(v)}$$

Then

$$C_j = Kf(v) = \frac{(C_t' - C_t)}{f(v') - f(v)} [f(v)] = \frac{C_t' - C_t}{\left(\frac{V + \phi}{V' + \phi}\right)^{1/n} - 1}$$

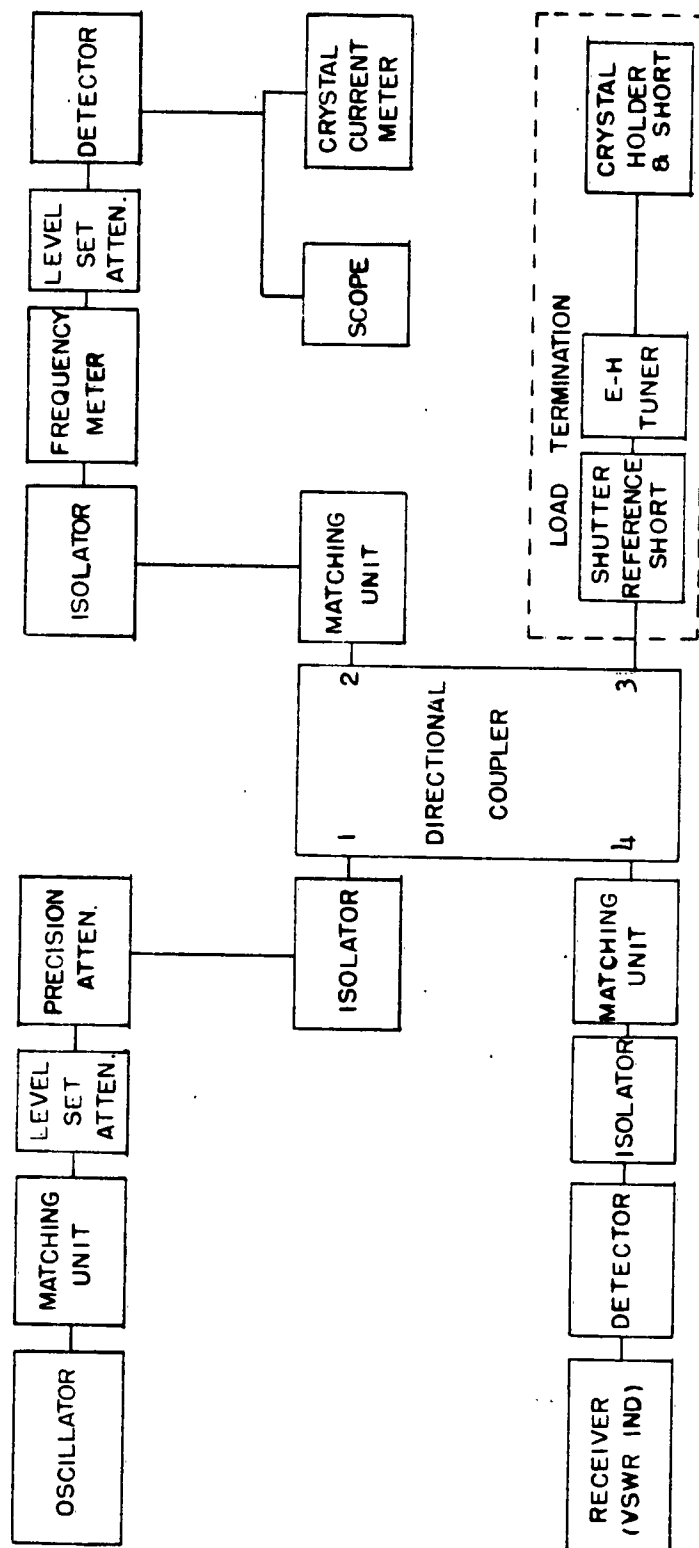


EQUIVALENT VARACTOR CIRCUIT
 (LOW FREQUENCY)
 FIGURE 1

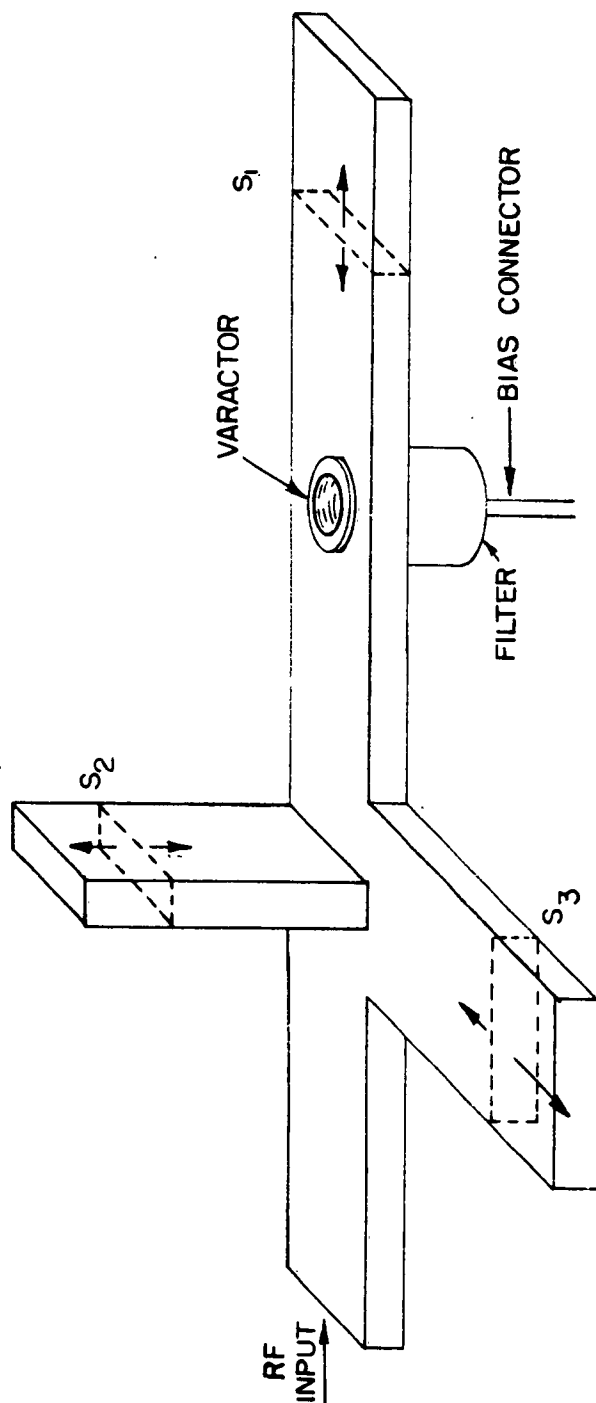


SIMPLIFIED EQUIVALENT VARACTOR CIRCUIT
(HIGH FREQUENCY)

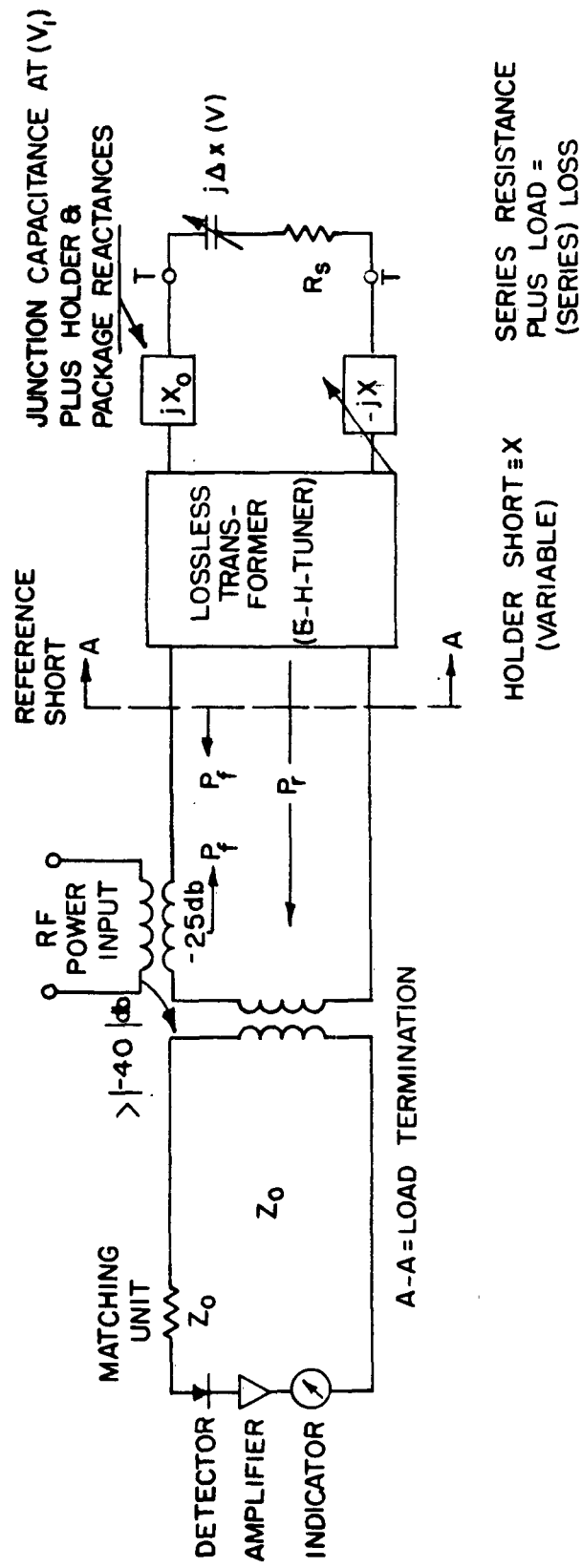
FIGURE 2



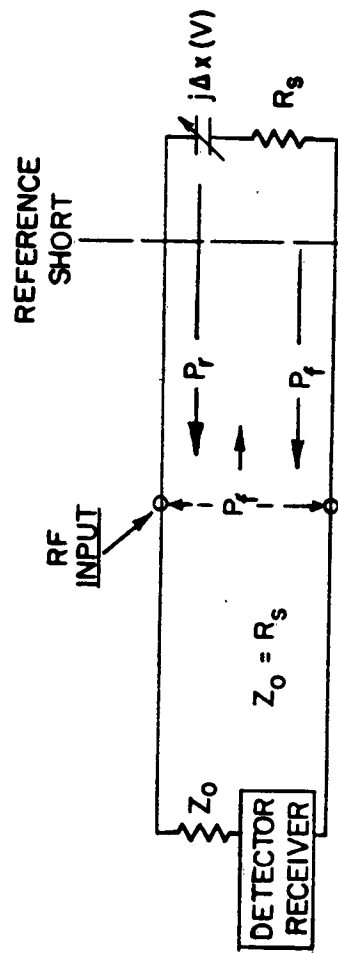
VARACTOR QUALITY MEASUREMENT
(BLOCK DIAGRAM)
FIGURE 3



E-H TUNER AND VARACTOR HOLDER
(MINUS CONNECTING FLANGES)
FIGURE 4



EQUIVALENT MEASUREMENT CIRCUIT
FIGURE 5



NORMALIZED EQUIVALENT MEASUREMENT CIRCUIT (SIMPLIFIED)
FIGURE 7

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DEVELOPMENT OF A QUALITY MEASUREMENT FOR
VARACTOR DIODES AT ALL MICROWAVE FREQUENCIES
by Frank P. Senko, November 1962, 16 p. incl. illus.
1 ref. (USAEURDL Technical Report 2282)
(DA Task 3499-21-001-02) Unclassified report

A technique is described for characterizing the microwave varactor diode at microwave frequencies. Basically, this is a reflectometer type of technique that permits reasonable accuracy and speed of measurement without the need for standard Smith Chart plots and/or auxiliary (substitute) devices. The varactor parameters of major importance are specified. Included also are the limitations of the method.

UNCLASSIFIED

1. Semiconductor Junction Characterization at Microwave Frequencies
2. Varactor Measurement at Microwave Frequencies
3. Microwave Characterization of a Nonlinear Reactance Diode

- I. Senko, Frank P.
- II. Army Electronics Research & Development Laboratory, Fort Monmouth, N. J.
- III. DA Task 3A99-91-001-02

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1. Semiconductor Junction Characterization at Microwave Frequencies
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3. Microwave Characterization of a Nonlinear Resistance Diode

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1 ref. (USAEIRDL Technical Report 2982)
(DA Task 3439-21-001-02) Unclassified report

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2. **Varactor Measurement at Microwave Frequencies**
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